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NASA TECHNICAL TRANSLATION NASA TT F- 14077

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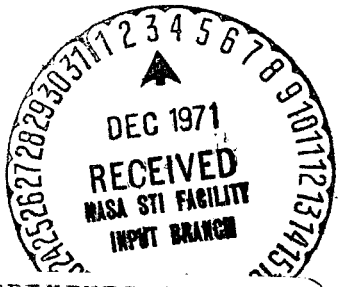
Paper presented at the 22nd International Astronautical Federation Congress, Brussels, September 1971, 14 pages



N72-12442 (NASA-TT-F-14077) NUMERICAL EXPERIMENTS ON LASER SOUNDING OF THE ATMOSPHERE FROM OUTER SPACE V.E. Zuyev, et al (NASA) Nov. 1971
Unclas 14 p CSCL 20E
09305 G3/16
FAC (NASA CR OR TMX OR AD NUMBER) (CATEGORY)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 NOVEMBER 1971

NUMERICAL EXPERIMENTS ON LASER SOUNDING OF THE ATMOSPHERE FROM OUTER SPACE

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The development of laser technique has made it possible to study successfully the composition and structure of the upper layers of the atmosphere on the basis of qualitative and quantitative analysis of backscattering, accompanying the light beam propagation. Optical echo from the altitude up to 120-140 km was registered in a series of experiments on laser sounding. Although the existent measurements are limited and have statistical nature, they confirm a conclusion about complex structure of the atmosphere in mesospheric and ionospheric regions. First, these conclusions are the essential inversions of aerosol concentration at the altitudes of 70-90 and 120-140 km, mesospheric clouds, clearly expressed accumulations of atomic nitrite at 80 km, etc. All these factors are prominent in formation of thermal and radiation balance of all the atmosphere as a whole.

In many cases, the investigation of small components of upper atmosphere by means of ground laser location cannot lead to reliable results due to screening influence of stratosphere and troposphere and limited energetic possibilities of lidars. The problem of investigation of electron density variations and cosmic dust layers at the altitudes over 100 km is far too involved. In this connection, the authors offer and analyze numerically the scheme of optical sounding from the outer side of the planet. The idea of lidar placing on the cosmic object of long duration, taken out beyond the scope of optically active earth atmosphere, forms the basis of this scheme. The altitude of sounding is taken equal to 300 km. Realization of this scheme will allow us to obtain practically undistorted echo signals from mesospheric and ionospheric formations; and conducting continuous measurements in movement along the path will allow not only high-altitude but also spatial properties of investigated objects to be estimated.

High complexity and cost of such an experiment makes it necessary to carry out a series of preliminary theoretical

investigations for selection of the equipment optimal parameters, wavelength range, measurement procedure, and echo signals interpretation. From the point of view of the radiation transfer theory, these investigations require solving the problem of estimating spatial-time structure of the light field reflected by spherical earth atmosphere in the direction of the emitter. The solution must be obtained for various, more probable optical models of media at different geometrical situations of the experiment.

The Monte-Carlo method, being good enough for numerical modeling of physical experiments, is used in the present paper to solve the given problem. This method makes it possible to solve a nonstationary problem of radiation transfer, taking into account the complicated boundary conditions appearing in real scheme of sounding and in non-uniform structure and composition of scattering media.

Special methods of random sampling[1], used in the computation algorithm makes it possible to overcome the systematic difficulties connected with estimation of weak light signals in small detector apertures. An optical transfer model being set in calculations incorporated numerical data for the interaction cross sections and single particle phase function of all the components of the atmosphere which give rise to scattering and absorption at chosen frequencies of lidar generations.

These tables reflect an altitude curve of the optical parameters mentioned. In this case, the altitude profiles of molecular and aerosol scattering coefficients were taken according to available reference data; and the single particle phase functions of mesospheric aerosol and cosmic dust were calculated in approximation of spherical absorbing particles according to the Mie formulas. At the altitudes above 140 km, where the Mie particles and molecular concentration is low, the scattering on free electrons becomes essential. The use of highly sensitive detectors doesn't exclude, in principle, the possibility to differentiate the layers with increased electron density in the ionosphere and thermosphere. Possible or observed sometime variations of aerosol and electron concentration in the altitude intervals mentioned above were set by introducing the coefficients of increased optical density zones into

appropriate tables. The examples of such optical models for λ = 0.69, 2.36μ used in a series of estimated variants are shown in figure 1. The data on molecular scattering and absorption for high altitudes are obtained by interpolation of known Elterman results[2], taking into account generally accepted standard models of the atmosphere.

A series of numerical experiments was realized using a BESM-6 computer, Computing Center SB AS U.S.S.R., using algorithmic language "alfa." The calculations were made for a series of laser wavelengths of visible and infrared range, in particular: =0.69; 1.06; 2.36. The choice of indicated wavelengths was due to the presence of high energetic ruby lasers, glass with neodymium lasers, and fluorite with dysprosium lasers. The results of statistical modeling that will be shown further have the meaning of discrete time signal scales, reflected by a given model atmosphere to a photon receiver located on the cosmic object. The photoreceiver dimensions were $\varnothing$= 30 cm, i.e., were close to the really possible ones. The developed algorithm allows the final geometrical parameters to be considered and the solution for some possible apertures of receiving optical system to be obtained simultaneously. This method makes it possible to estimate the influence of various atmospheric components (aerosol, water vapor, gas components) on the formation of radiation field and its time characteristics. There is a possibility of separation of resulting photon runs, entering the detector, according to their multiplicity of interaction with medium.

Let's turn to the results of statistical experiment. Figure 2 shows the time histogram of 30 nsec signal duration reflected by all the thickness of the atmosphere for the wavelength λ = 0.69μ. According to the previous figure, the regions of increased aerosol concentration suitable to the altitudes of noctilucent clouds and observed sometimes cosmic dust layers (120-140 km) were set in the optical model. For convenience in consideration, the values of equivalent altitudes were plotted against left Y-axis in the figure. The mesh of histogram points is uniform with spacing of altitude Δh= 5 km. The values of counts are listed both in relative units, i.e., the result is fixed to the source power P=1 photon/pulse, and in energetic ones for conventional lidar with energy of one

pulse P=0.5j and quantum efficiency η=1.0. The result for a series of pulses in the accumulation scheme will obviously meet the condition of additivity. The values of various functionals shown in the figure resemble values of complete photoreceiver aperture φ=40′ 180°. A signal due to back-scattering of molecular component is separated. Given the values of layer optical thicknesses of aerosol inversion ($\tau_{NLC}=0.6\div10^{-3}$ and $\tau_{CD}=0.5\div10^{-4}$) shown in the figure, they are clearly identified in the time scale of the reflected pulse. This gives grounds for the conclusion that the signal from them in real experiment will be separated at general level at much less optical density. Comparing the given results with the preceding numerical experiment on sounding of mesosphere from the earth surface[3], we may note an interesting physical detail. The background of multiple scattering, i.e., signal addition in 180° aperture, while sounding the scattering medium with gradually increased optical density, appears to be shifted along time coordinate beyond the information zone. And, as for the inverse situation which takes place while sending a signal to the atmosphere from the earth, the contrary infavorable picture originates: At the cost of multiple scattering in the lower, more dense atmosphere, the photons "are late" and give the contribution to those parts of time scale of the signal which correspond to higher altitudes. This fact distorts the signal being received, imposes more serious requirements to the photoreceiver aperture, increasing energy costs of the experiment as a whole. In all the numerical experiments performed for various models of clear atmosphere, the maximum of the reflected signal corresponded to the earth surface level. Further follows "multikilometer tail" of the pulse trailing edge due to multiply scattered photon runs. The length of the pulse trailing edge is defined by the receiver aperture. Figure 3 shows the results of numerical modeling of photon distribution according to their runs, obtained for the same wavelength λ=0.69μ for three values of the detector aperture: φ=40′ 10°; 180°. Aerosol model of the atmosphere in this calculated variant is a smooth monotonically decreasing one with the altitude. The variation of the earth surface albedo within the limits 0.2-1.0 does not result in the marked changes of the shape of exponentially decaying signal trailing edge. As it is shown in Figure 4, only the decrease of background level

owing to radiation absorption of the earth surface takes place. Given sufficiently small photoreceiver apertures $\varphi \leq 5^{\circ}$, the signal value, reflected by the earth surface, is determined with good accuracy only by spectral transmission of the atmosphere and albedo value. This single-valued relation opens the way for appropriate calibration of photodetectors under conditions of real experiment for continuous measurement of albedo of various underlying surfaces. However, the estimates are valid only for a model of transparent clear atmosphere. The influence of cloudiness at low altitudes requires additional investigations.

Figure 5 shows statistical estimates of backscattering of the earth's atmosphere (strato-heterogeneous model, Figure 1) for a wavelength $\lambda = 2.36\mu$. The signal value due to the scattering by molecular component is shown separately. The absorption by water vapor is not taken into account for lack of data on the absorption coefficients in this wavelength range. As usual, an artificial increase of aerosol scattering coefficients at altitudes 80 - 85 km and 110 - 140 km results in appearance of certain echo-signals from these parts. The influence of molecular scattering becomes negligible even in the bottom layers of the atmosphere. Typical properties of time profile are kept as a whole, the contrast of a signal from the earth surface slightly increases. In histogram breaks, the values of estimates fall outside the limits of scale mesh of the plot. A signal from the atmosphere above 140 km was lacking in all the cited numerical experiments, evidently owing to extremely low optical density of thermosphere in the wavelength range covered.

Figure 6 shows the time profile of a backscattered signal at the wavelength $\lambda = 1.06\mu$. The layers of cosmic dust were not given in the model, aerosol model of the atmosphere is a standard one, close to the data by Elterman[2].

It should be mentioned in conclusion that statistical error of the given estimates depended on the value of functionals being estimated. It is essentially worse for weak signals from the upper atmosphere with small receiving apertures.

Relative error, being on the average 10-15 percent, here amounted to 30÷40 percent. The time of modeling of 250 thousand random experiments, which result in such statistical convergence of the result, was on BESM-6 computer on the average 25÷35 minutes.

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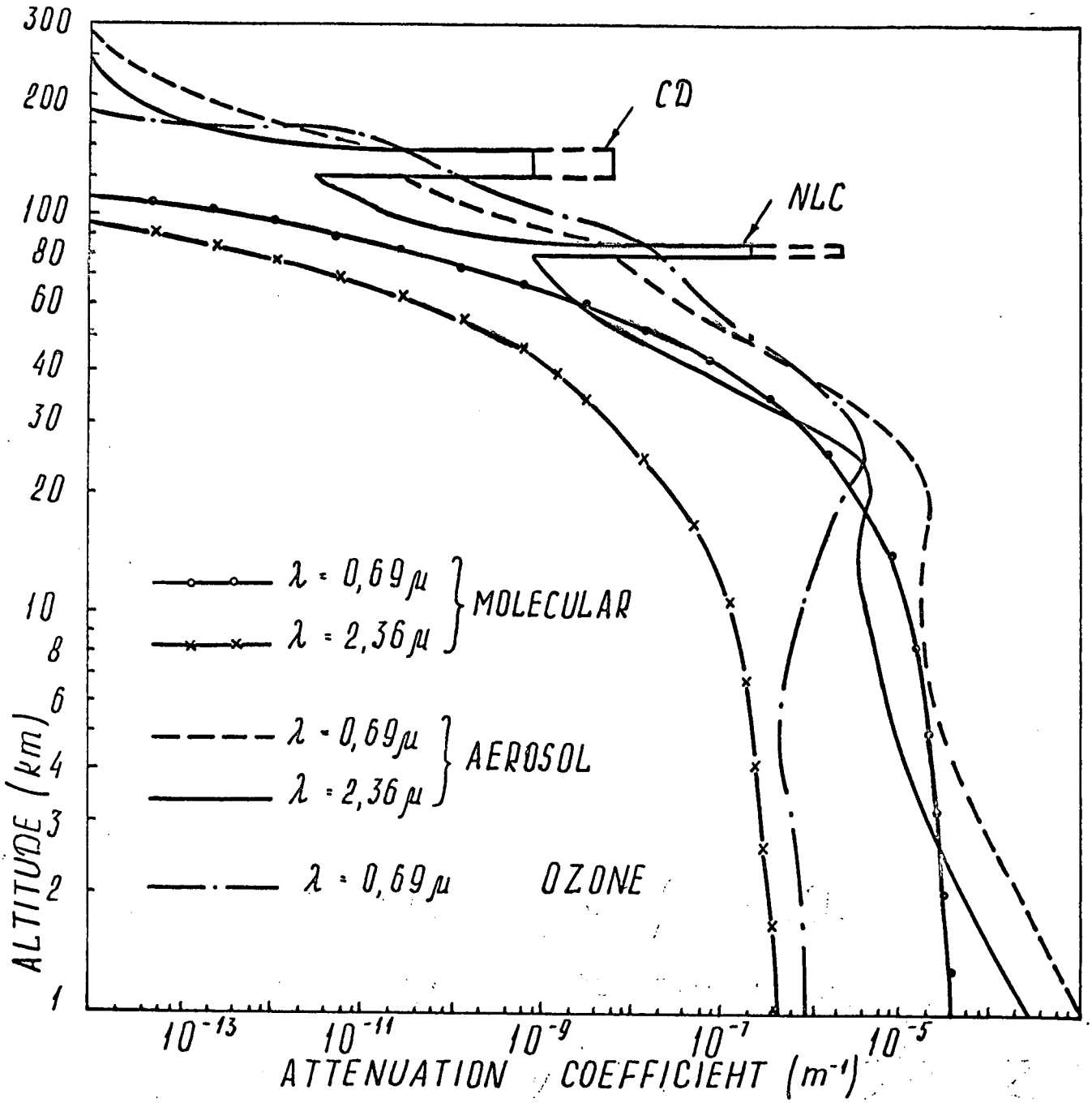

FIGURE 1. Optical Models of the Pure Atmosphere Used in the Numerical Experiments.

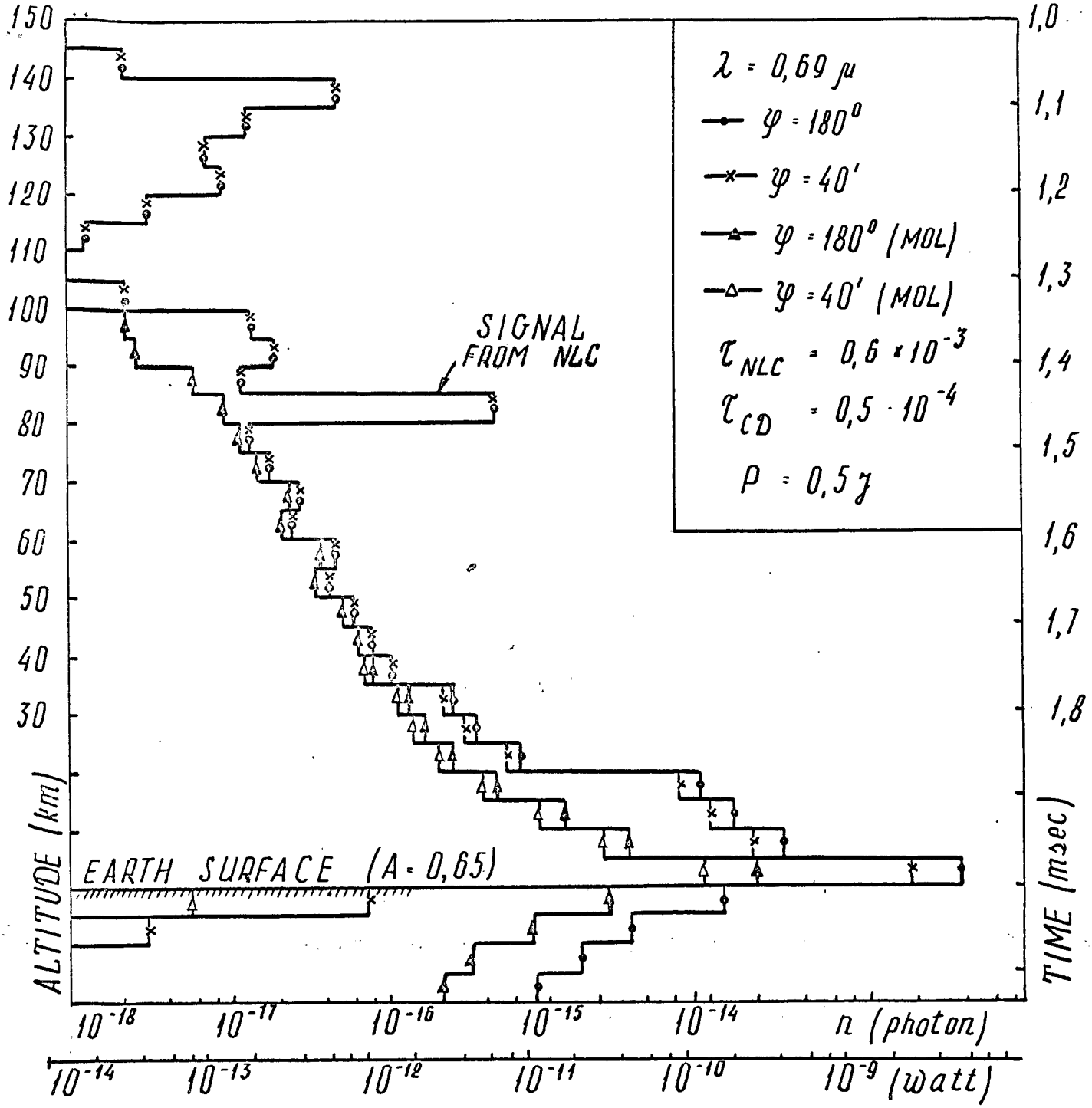

FIGURE 2. Detected Photons as Function of the Time and Altitude of Scattering in Presence of NLC and CD for the Lidar at 0.6943 μ.

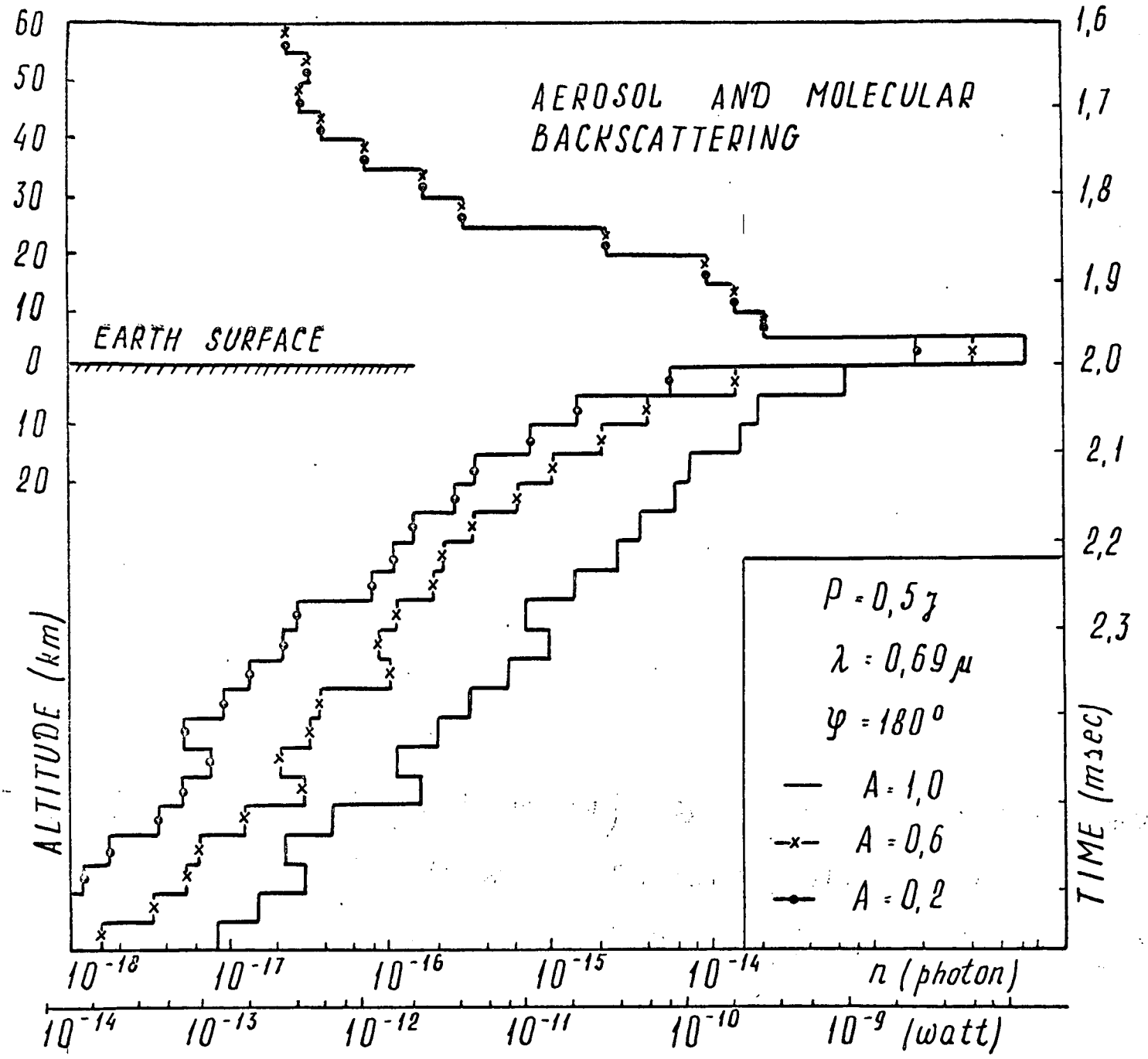

FIGURE 3. Change of the Light Backscattering Profile versus Aperture of the Detector.

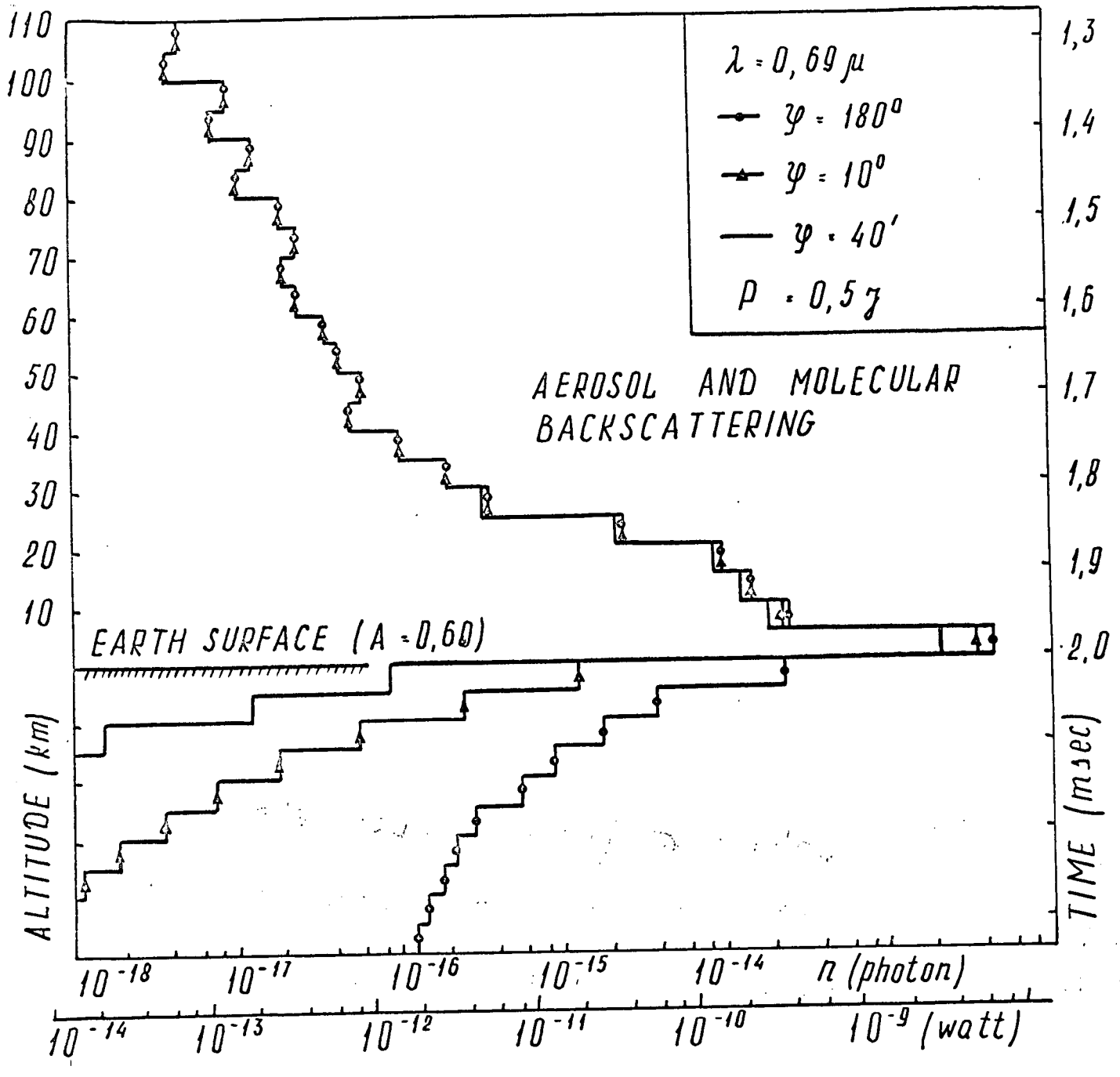

FIGURE 4. The Influence of the Earth Surface Albedo on the Light Backscattering Profile.

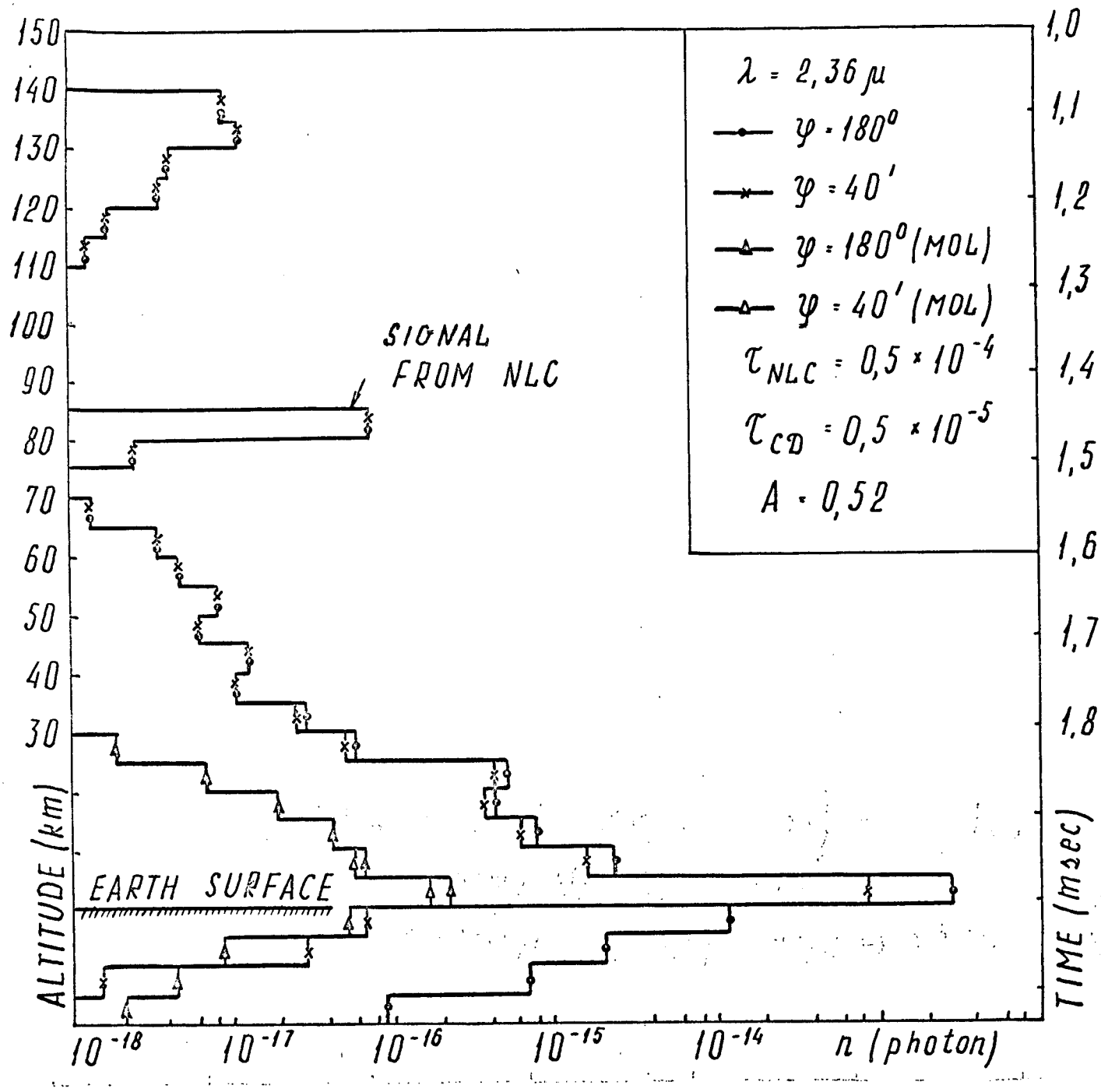

FIGURE 5. Detected Photons as Function of the Time and Altitude of Scattering for Lidar at 2.36 μ.

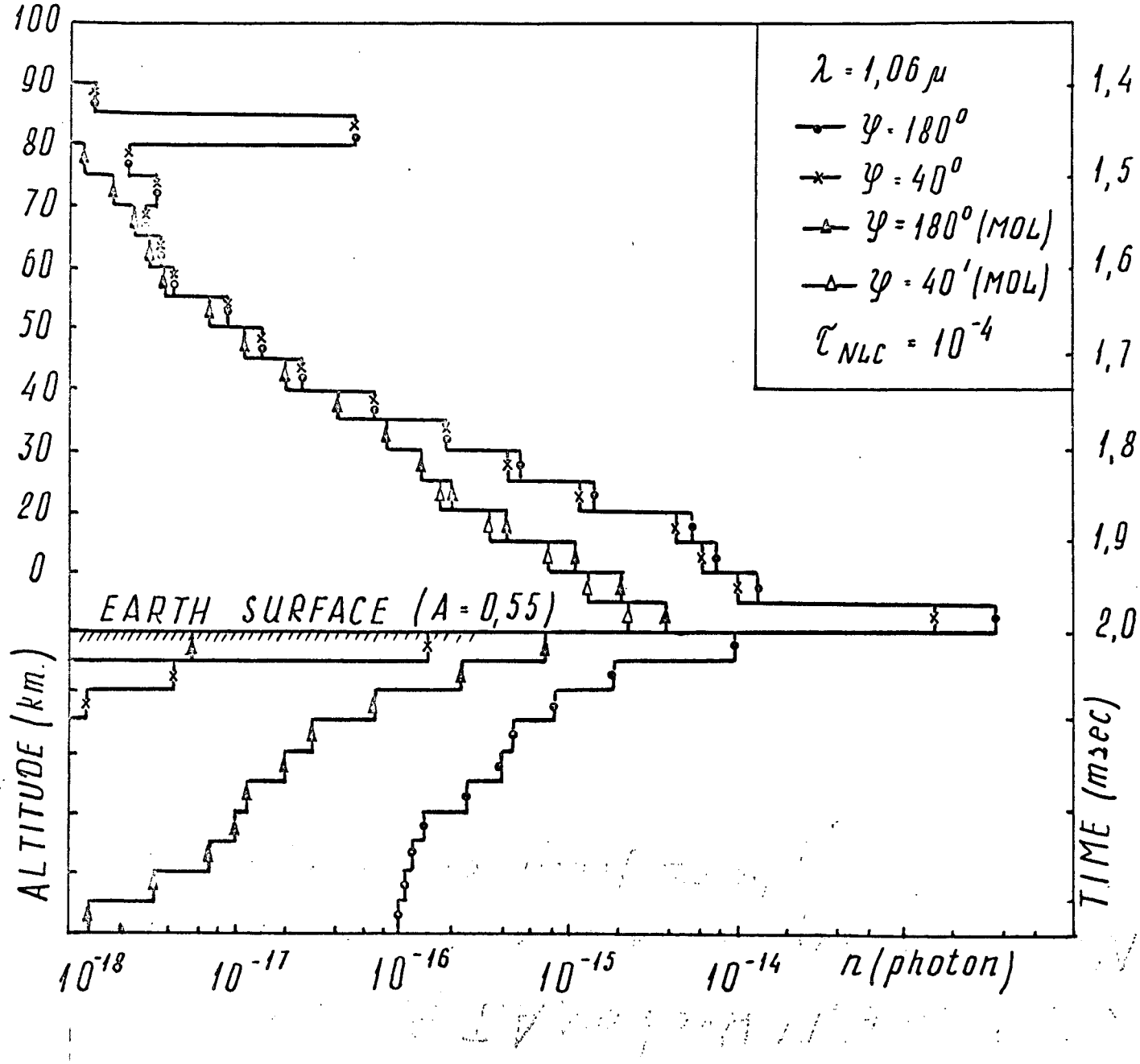

FIGURE 6. The Same Results for Lidar at 1.06 in Presence of NLC Only.